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ON THE CHARACTERISTICS OF NON-LINEAR SOIL RESPONSE AND DYNAMIC SOIL PROPERTIES USING VERTICAL ARRAY DATA IN JAPAN

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SUMMARY

Non-linear response of the soil is investigated by comparing the spectral ratios (uphole/downhole) using weak and strong motions. Data from seven vertical arrays in Japan are analysed in this study. The frequency-dependent transfer function of soil is calculated as a ratio of the spectrum at uphole to the spectrum at downhole, considering the horizontal component of shear wave. In spectral ratio analysis auto- and cross-spectra are employed. The reduction in the predominant frequency of the transfer function with increases in excitation level reflects the non-linear response of the soil. Results of analysis demonstrate a significant non-linear ground response at six sites with surface PGA exceeding 90 gal. However, the results of one site show the linear response up to 130 gal surface PGA. Furthermore, the *in situ* strain-dependent soil behaviour is examined through the shear modulus – shear strain relationship. When compared, the actual and laboratory results of the shear strain – shear modulus relationship are in agreement. Additionally, a good consistency between the tendency of reduction in shear modulus ratio with shear strain increases, and reduction of predominant frequency with ground motion increases, confirms the significance of non-linearity in site effects study.

KEY WORDS: vertical array; weak and strong ground motions; transfer function; auto- and cross-spectra; non-linear soil response; *in situ* dynamic soil properties

INTRODUCTION

The distribution of earthquake damage clearly reveals that the characteristics of earthquake ground motion depend strongly on the site effects. An earthquake motion can be amplified at certain frequencies depending on the physical properties of the soil. Also, soil materials show remarkable non-linearity in their stress–strain relationship. Therefore, it is important that the non-linear property of soil be taken into account in the analysis of site response during strong earthquakes. Consequently, investigation of the actual characteristics of soil response to seismic loading is an important aspect of earthquake engineering.

Non-linear soil behaviour, occurring as the excitation level increases, is confirmed by numerous experimental results performed on soil samples as a typical hysteretic form.[1,2] However, it has been under the assumption that the *in situ* materials behave similarly to soil samples. Idriss and Seed showed that surface deposits reveal non-linear behaviour with increased damping and decreased shear wave velocity.[3] On the other hand, seismologists neglect the non-linear effects of soil in practical applications due to limited observable evidence of the non-linear soil response from actual strong motion records.[4,5] Additionally, when compared to non-linearity, the linear elastic approach is far more simple and powerful tool in solving seismological problems. Accordingly, the non-linear soil response in strong ground motion has been controversial subject between seismologists and earthquake engineers.[6–10]

Recently, a rapid increase in the number of permanent strong motion arrays, especially vertical arrays, and improvement in data quality was made at an international level. The vertical array data in a non-linear study

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is favourable since the problem of source and path spectral contributions, which are a main obstacle to identifying non-linear site effects using the spectral ratio from the spectrum of one site to that of the reference site, can be strongly overcome.[11] This is due to the fact that the distance between uphole and downhole instruments is negligible for the source radiation and the wave propagation path effects, which often overshadow the non-linearity. Hence, the interest in studying the aspects of soil response to strong motions is increased. Besides, the need for determining the actual dynamic properties of *in situ* soil has been emphasized because of significant influence on the evaluation of ground response.[12] Shear modulus measured in the laboratory has often been compared with those measured *in situ* for low shear strain (about 10^{-6}). However, it still seems unclear whether the laboratory data could duplicate *in situ* soil behaviour up to the large shear strain prevailing during large earthquakes. In this paper, the analysis of non-linear soil response and actual dynamic soil properties, in seven vertical arrays in Japan with different sedimentary strata and depths, are described.

EARTHQUAKE DATA AND SITE CONDITIONS

The locations of seven Japanese sites with vertical array accelerographs, considered in this study, are shown in Figure 1. Detailed descriptions of soil parameters for the sites at which the geotechnical and geophysical field explorations have been carried out are given in Table I.[13–15] In each site, the three components of acceleration are installed at different depths. The NS component of acceleration in depths of 10, 100, 30, 40, 28, 100 and 44 m is used in Chiba, Etchujima, Fujisawa, Samukawa, Shinfuji, Tomioka and TTRL sites, respectively, for spectral ratios presented here. The data were recorded digitally at the rates of 50, 100 and 200

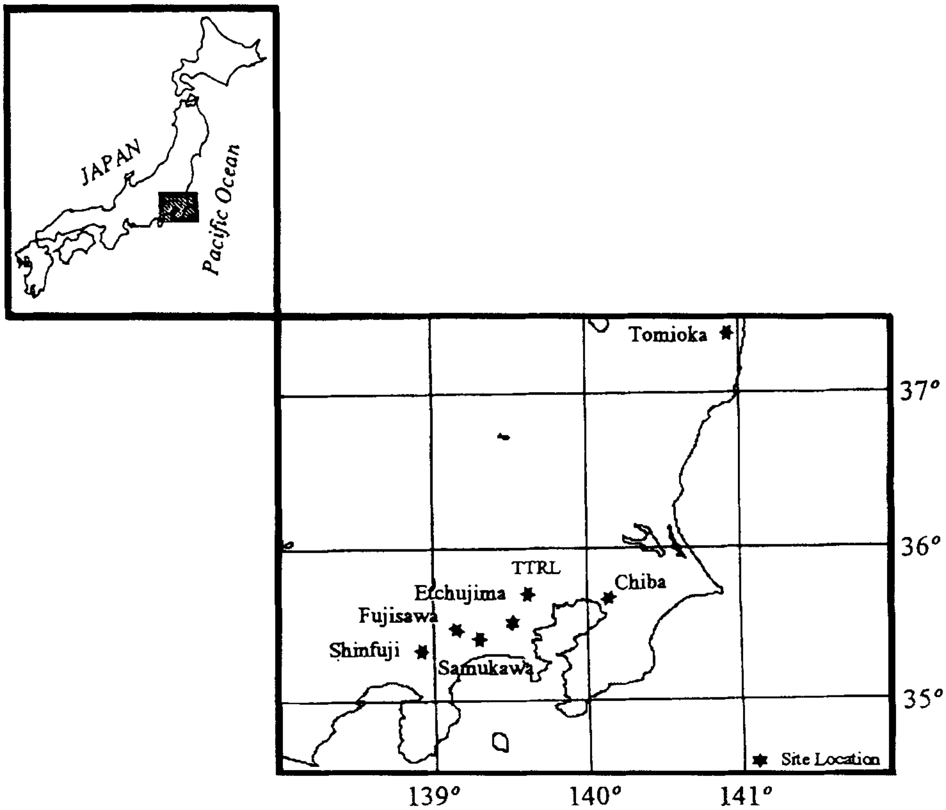

Figure 1. Map of Japan and the location of vertical array sites

Table I. Soil parameters of vertical arrays

Depth (m)	Soil type	V_p (m/s)	V_s (m/s)	Density (g/cm^3)
		Chiba site		
1–5	Loam	320	140	1·38
5–10	Sandy clay	550	320	1·50
		Etchujima site		
1–11	Silt	940	110	1·70
11–16	Clay	1330	130	1·60
16–26	Silt	1330	130	1·70
26–37	Silt	1200	230	1·70
37–83	Sand	1750	380	1·85
83–100	Bedrock	1750	460	1·90
		Fujisawa site		
1–16	Humus	1000	40	1·13
6–22	Silt	1500	65	1·42
20–22	Silt	1500	100	1·58
22–25	Clay	1900	400	1·58
25–30	Sand	1900	400	1·81
		Samukawa site		
0–5	Silt	750	110	1·55
5–10	Gravel	530	300	1·98
10–22	Sand	1330	300	1·85
22–31	Silty clay	1550	230	1·84
31–40	Sand	1620	370	1·72
		Shinfuji site		
1–7	Loam	300	130	1·47
7–14	Loam	640	250	1·68
14–24	Loam	870	412	1·69
24–28	Loam	1240	726	1·95
		Tomioka site		
0–74	Sand	1800	520	1·55
74–100	Sand	1800	700	1·65
		TTRL site		
3–28	Silt	1,150	150	1·71
28–44	Clay	950	220	1·61

Note: The soil parameters are given up to the depth used in spectral ratio analysis in each array

samples per second. The analysed earthquakes are selected from Strong Motion Array Recorded Database in Japan published by the Association for Earthquake Disaster Prevention.[14]

The smallest and largest possible earthquake data have been selected for most sites. On the contrary, only the largest earthquakes with 170 and 130 gal (cm/s^2) surface PGA (Peak Ground Acceleration) are used for Samukawa and Tomioka sites, respectively. The length of the recordings at these sites makes it possible to derive the transfer function of weak motion by using the end parts of the records. Parameters of the events selected for the analysis are listed in Table II. The surface PGA of strong motions extend from 80 to 416 gal.

Table II. Selected events in seven vertical arrays for analysis

Event no.*	Date yr.m.d.	Depth (km)	M	Δ (km)	PGA (Gal)	Signal-to-noise ratio	Name of vertical array
1	1989·03·06	55	6·0	55	28·9	86	Chiba
2	1987·06·30	56	4·9	62	33·5	105	Chiba
3	1987·12·17	58	6·7	45	301·1	1,654	Chiba
4	1983·08·08	22	6·0	72	20·5	85	Etchujima
5	1983·02·27	72	6·0	44	60·1	89	Etchujima
6	1987·12·17	58	6·7	71	86·5	87	Etchujima
7	1988·03·18	96	6·0	14	95·3	67	Etchujima
8	1982·02·23	50	5·4	241	1·6	5	Fujisawa
9	1983·08·08	22	6·0	44	91·6	136	Fujisawa
10	1989·10·14	21	5·7	61	170·1	5,613	Samukawa
11	1982·08·12	30	5·7	77	40·5	224	Shinfuji
12	1983·08·08	22	6·0	18	416·7	2,077	Shinfuji
13	1983·07·02	54	5·8	51	132·8	568	Tomioka
14	1987·04·07	44	6·6	258	13·5	16	TTRL
15	1983·08·08	22	6·0	74	14·4	26	TTRL
16	1983·02·27	72	6·0	42	60·9	253	TTRL

* Event number does not correspond to the original classification and is a given number
Δ: Epicentral distance

Figure 2 shows some examples of recorded events at uphole and downhole in Chiba, Fujisawa and Shinfuji sites. Table II shows an estimate of the apparent signal-to-noise ratio of uphole records at each site. This ratio was determined by dividing the rms of a 10 s segment of the shear wave by the rms of the post-event noise. Events 10 and 8 had the highest and the lowest signal-to-noise levels, respectively. Furthermore, the power spectrum of noise and signal with the spectral noise-to-signal ratio were calculated as shown in Figure 3 for events 9 and 12. The spectral ratios of noise-to-signal highlight the significance of noise in the frequency range of 0–0·20 Hz.

METHOD OF ANALYSIS

The surface layer overlying a rigid basement exhibits the predominant resonance frequency[2] (f) at $f = v/4h$, where v is the shear wave velocity of the surface layer, and h is its thickness. Thus, the resonance frequency of the layer is proportional to the wave velocity and will be shifted downward as the strain increases. Because of this proportional relationship, the non-linear soil response can be investigated in the form of reduction in resonance frequency of the soil with increases in the level of motion. Consequently, if an earthquake record is divided into several time windows (i.e. different levels of shaking), the reduction in resonance frequency of soil transfer function should be seen as the level of shaking increases in those time windows.

The transfer functions of soil can be obtained by the uphole to downhole spectral ratio for different time windows of the record. In spectral ratio analysis auto- and cross-spectra are introduced. The auto- and cross-spectra can reveal the true characteristics of the site, especially predominant frequency, due to effective removal of input and output noise.[15] Here, the non-linear soil response analysis is mainly addressed using the predominant resonance frequency (for simplicity, hereafter referred to as resonance frequency). Accordingly, accelerograms recorded at uphole and downhole were divided into a number of 10·24 or 5·12 s time windows representing different levels of shaking. The time window divisions were used between the S-wave arrival and, generally, the end of the record.

The spectral ratio is calculated using the following procedure for each time window: (1) The cross- and auto-spectra are calculated; (2) the spectra are smoothed using a rectangular average filter having a band

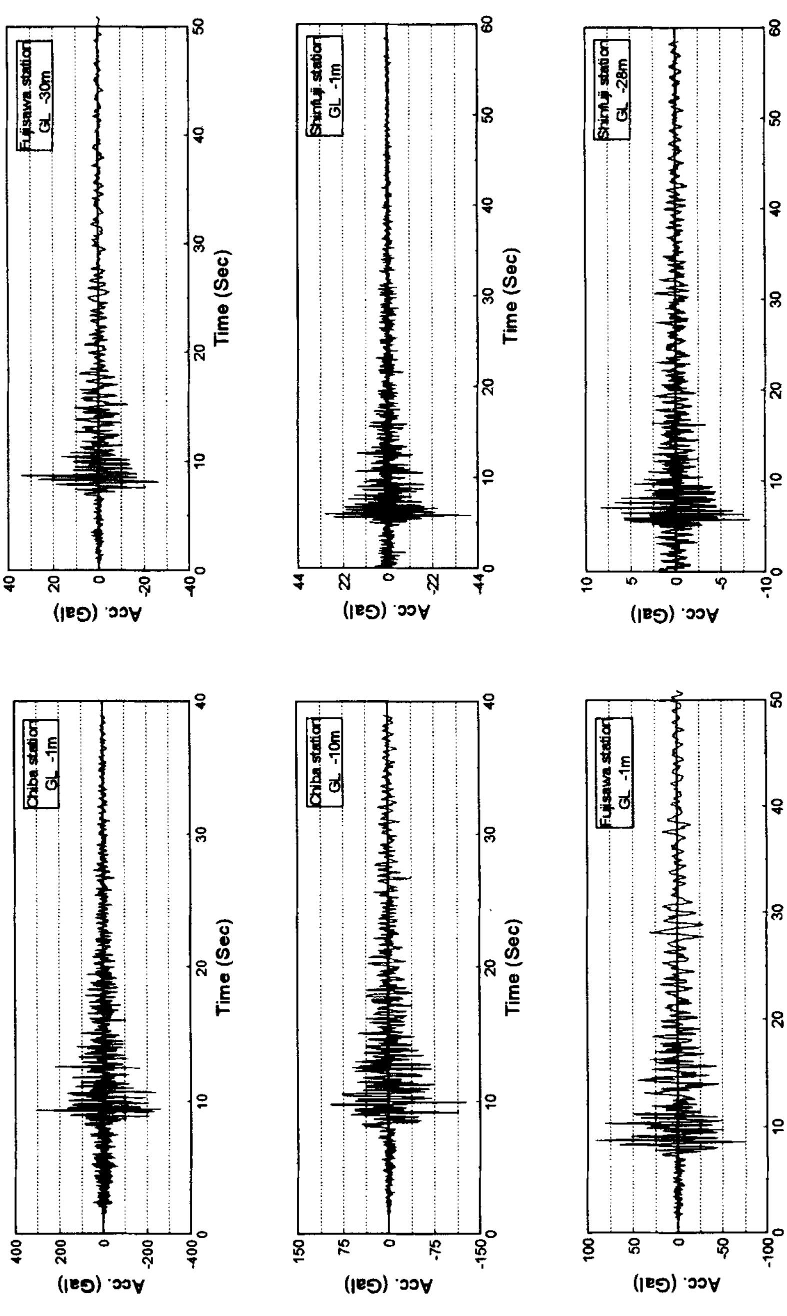

Figure 2. Uphole and downhole accelerograms in the NS direction for events 3, 9 and 11 in Chiba, Fujisawa and Shinfuji sites, respectively

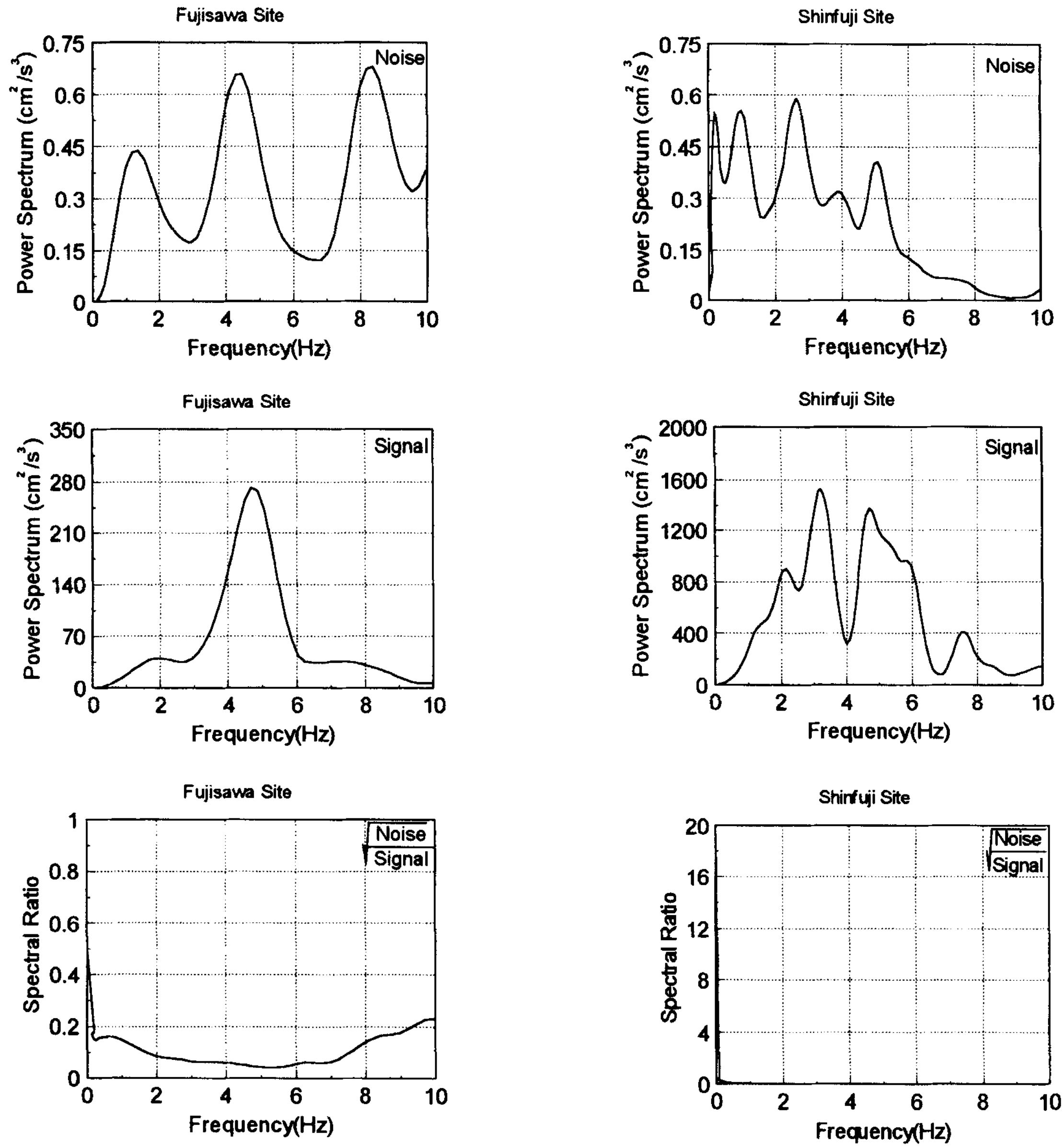

Figure 3. Power spectra of noise and signal as well as noise-to-signal spectral ratio ($\sqrt{\text{Noise/signal}}$) for events 9 and 12 at Fujisawa and Shinfuji sites, respectively

width of approximately 0·5 Hz; (3) the ratio of two smoothed spectra is calculated; (4) the square root is taken from the spectral ratio. Three times in succession smoothing was applied to the raw spectra. This number was chosen empirically considering its visual effect on the spectral shape. Figure 4 shows an example of the transfer functions for events 3, 9 and 11 in Chiba, Fujisawa and Shinfuji sites respectively. In addition, to show strain-dependent non-linear soil properties, the strain is calculated from the relative displacement between uphole and downhole readings divided by their distance. The base line correction is also applied in the calculation. Figure 5 shows the results of calculated strain time histories between uphole and downhole at the depths of 10, 30 and 28 m for events 3, 9 and 11, respectively, for the above sites.

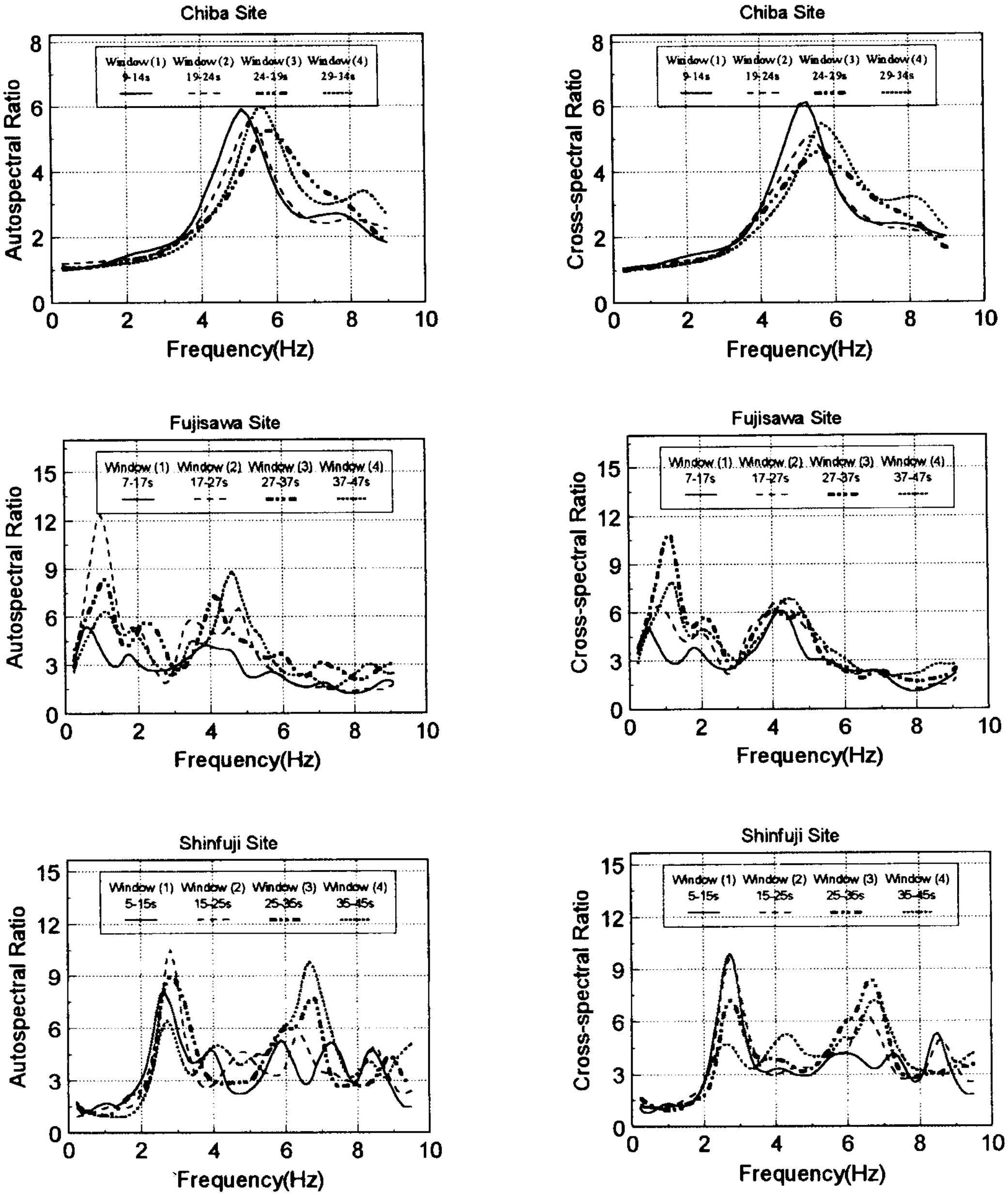

Figure 4. The transfer functions calculated by using auto- and cross-spectra for different time windows of events 3, 9 and 11 in Chiba, Fujisawa and Shinfuji sites, respectively

RESULTS AND DISCUSSIONS

In Figure 4, the examples of transfer functions calculated by spectral ratio analysis using auto- and cross-spectra are shown. The transfer functions at each frame belong to the different 5·12 s time windows for the Chiba site and 10·24 s time windows for the Fujisawa and Shinfuji sites. The decrease in resonance frequency can be seen in the time windows going from the end to the beginning of the record (corresponding to an increase in the level of shaking) for events 3 and 9 with 301·1 and 91·6 gal PGA. However, the resonance

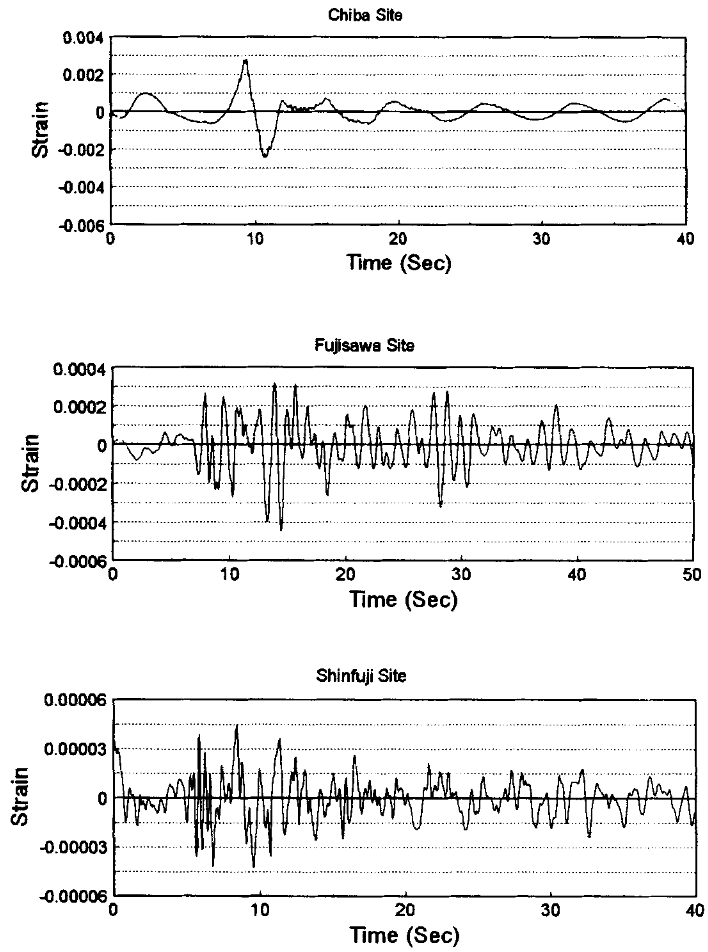

Figure 5. Strain time histories derived from uphole and downhole accelerograms for events 3, 9 and 11 in Chiba, Fujisawa and Shinfuji sites, respectively

frequency seems unvarying for the event 11 with 40·5 gal PGA. The reduction in the resonance frequency with increasing level of shaking manifests the non-linear response of soil in Chiba and Fujisawa sites for events 3 and 9, respectively.

The comparison of resonance frequencies calculated by cross- and auto-spectra shows that the results of these two techniques are quite consistent. Furthermore, the stability of results is examined by a variety of data samples. These facts confirm the accuracy in calculating the resonance frequency for each time window. The authenticity of using the end part of the strong motion record (coda of strong shear wave) as a weak motion is proved by comparison of transfer functions derived from the coda part of strong motion and weak motion (small earthquakes) as shown in Figure 6. As can be seen, the amplification functions are in good agreement, especially for resonance frequency. This suggests that the amplification function calculated from the coda part of strong motion is a good approximation for weak motion amplification function.

In Figure 7, the transfer functions obtained for the largest and smallest levels of shaking from the time windows analyzed for all events at each site are shown. A shift of the resonance frequency in the range of 0·3–1 Hz is clearly seen in this figure. However, there is no remarkable change in the resonance frequency of Tomioka site which suggests a linear response. In spite of the evident shifting in the resonance frequency with

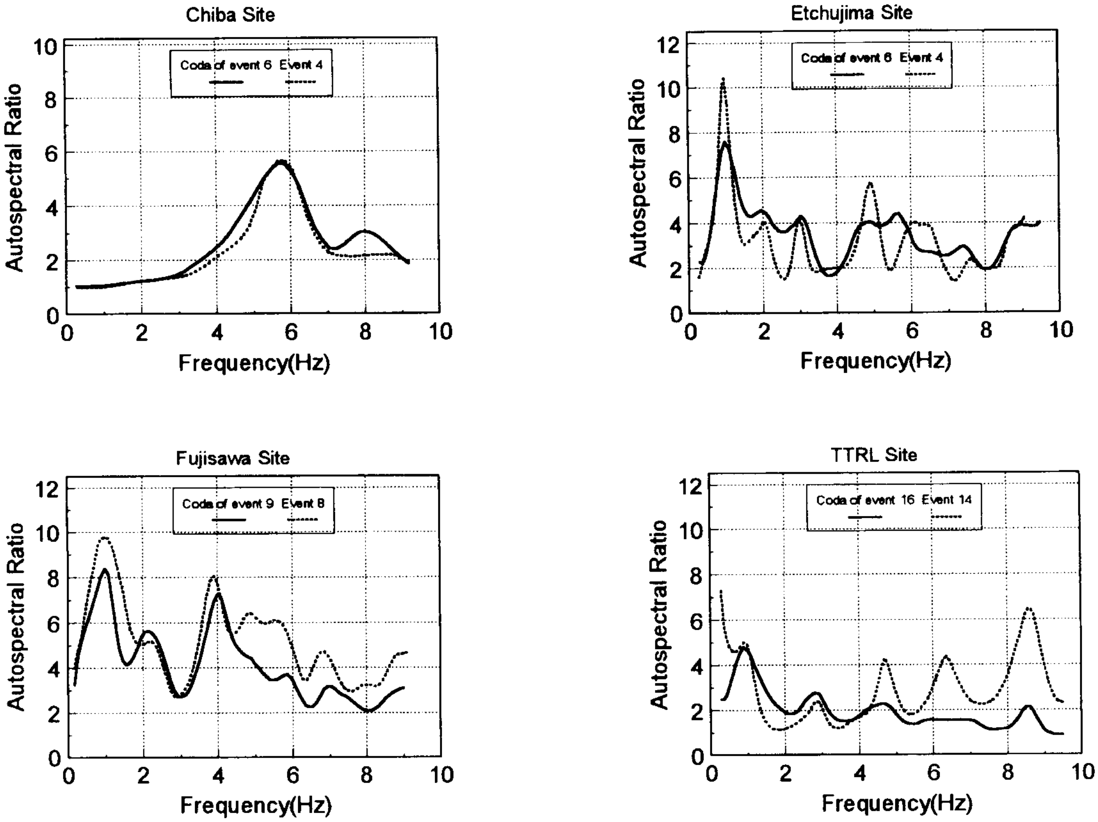

Figure 6. The transfer functions from the coda part of strong motion and records of small earthquake in Chiba, Etchujima, Fujisawa and TTRL sites

the level of shaking, there is no clear trend of deamplification effect in spectral ratios of different time windows for each earthquake (Figure 4, Chiba site). Nevertheless, the spectral ratios derived from the smallest and largest shaking level time windows (Figure 7) expose the clear deamplification in the Chiba and Shinfuji sites, where the strong motions of 301·1 and 416·7 gal, respectively, were analysed. Whereas, there is no observable deamplification effect in Etchujima, Samukawa and TTRL sites. The explanation for such an inconsistency is not apparent at this time.

Based on the above results, it is possible to investigate the actual soil behaviour up to relatively large shear strains. For this purpose, the resonance frequencies obtained from transfer functions of different time windows for all events, at each site, are divided by the largest resonance frequency obtained among them. From the resonance frequency ratio, f/f_0, the shear modulus ratio can be given as $f/f_0 = v/v_0 = \sqrt{G/G_0}$, where v/v_0 and G/G_0 are velocity and shear modulus ratios, respectively. For evaluation of strain, the calculated strain time histories are divided into the windows corresponding to the time windows which are used in the spectral ratio analysis. The shear modulus ratio is related to the maximum value of strain in the same time window. This procedure is repeated for all sites, and the calculated shear strain–shear modulus relationships are shown in Figure 8. There is a fairly well-defined trend in which the shear modulus ratio decreases with the increasing shear strain. In addition, results of the shear strain–shear modulus relationships for all sites are combined in Figure 9. Comparison of the actual and laboratory results [2,17–21] in Figure 9 demonstrates good agreement between the actual and experimental ones especially in the shear modulus reduction behaviour.

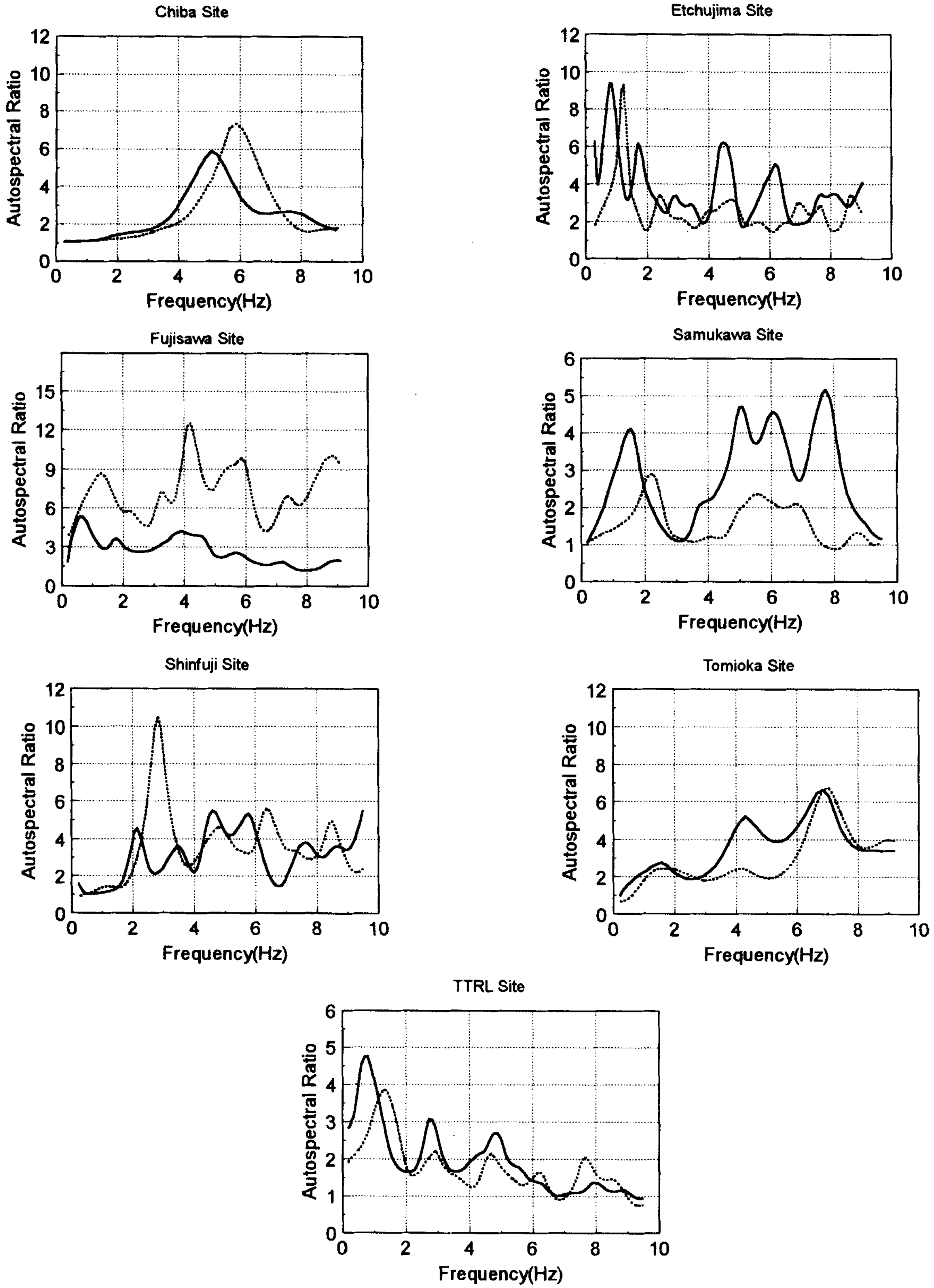

Figure 7. The transfer functions of the largest (continuous line) and smallest (dotted line) shaking level time windows from the analysis of all events at each site

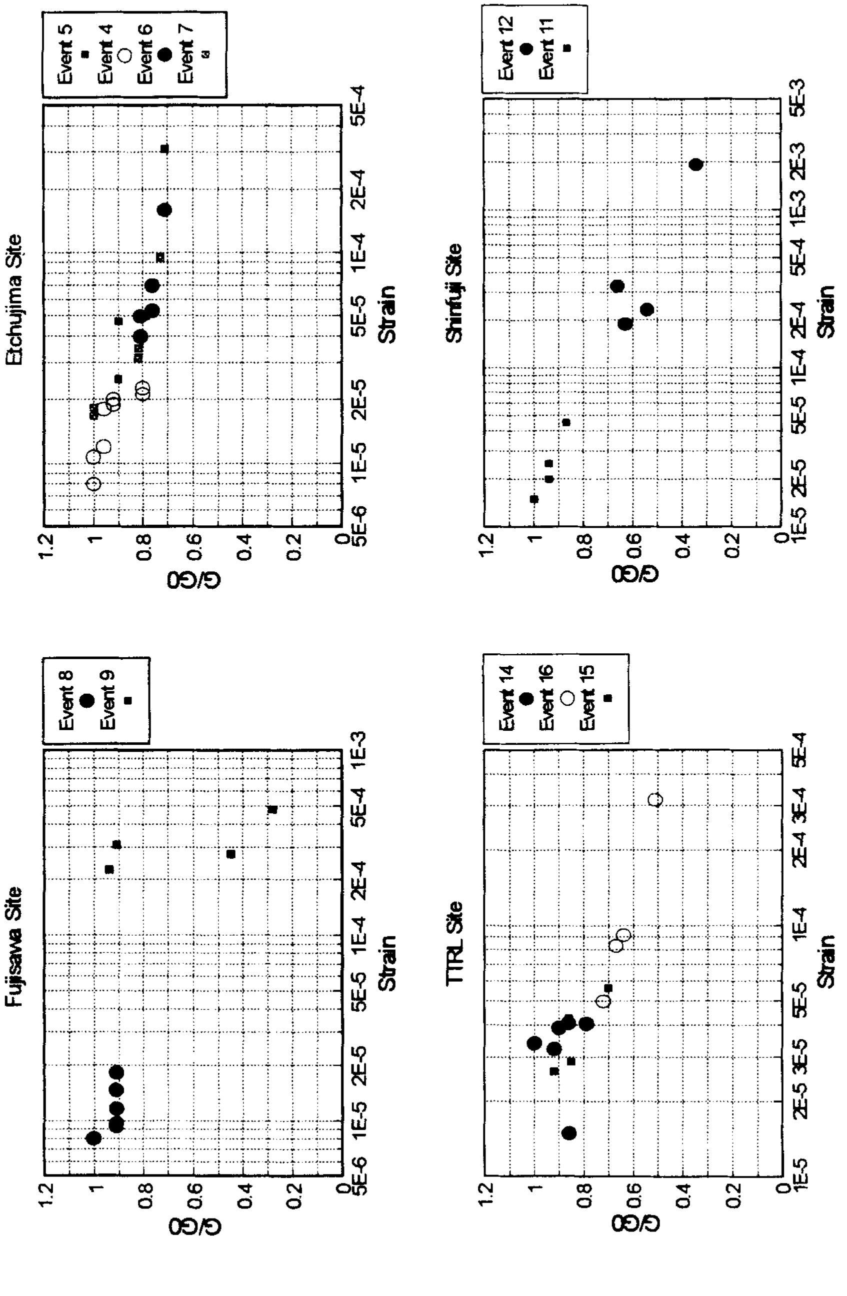

Figure 8. *In situ* shear strain–shear modulus relationships from the analysis of all events at each site

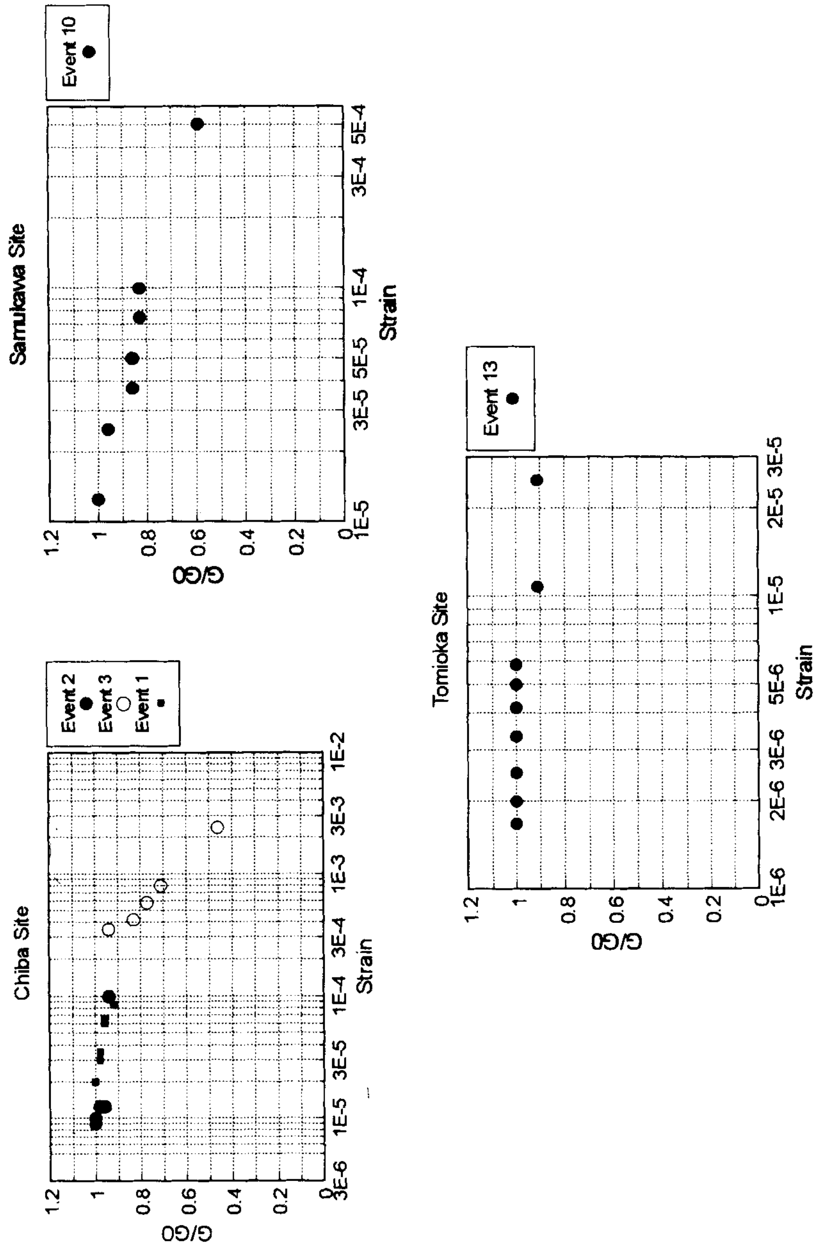

Figure 8. (continued)

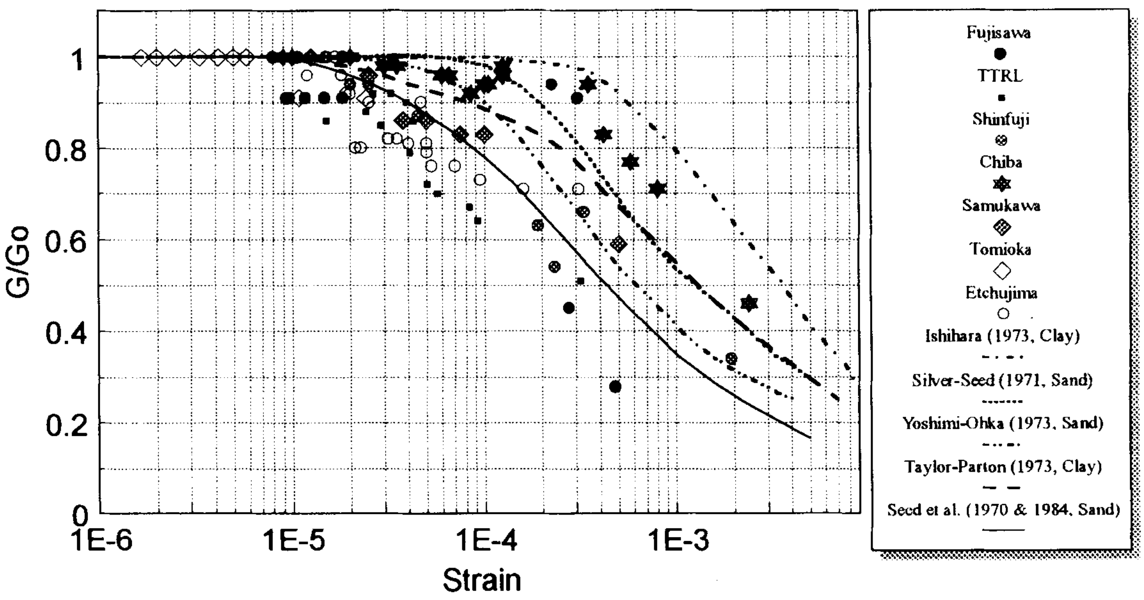

Figure 9. Comparison of *in situ* shear strain–shear modulus relationships of all the sites and experimental results

CONCLUSIONS

In this study, the amplitude-dependent site amplification effects are investigated using the data of seven vertical arrays in Japan. Furthermore, an attempt is made to examine the actual *in situ* dynamic soil behaviour in these sites. For these reasons, the soil response on weak and strong ground motions are compared using uphole/downhole spectral ratio. For the most part, the whole length of data after S-wave arrival is investigated in this analysis by using 10·24 s or 5·12 s time windows.

The resonance frequencies obtained from spectral ratios at different time windows display a clear change with the level of ground motion shaking. Furthermore, the direct comparison of transfer functions derived from the coda part of strong motions and independent small earthquakes showed that the coda amplification can be regarded as an amplification of weak motion. The above facts suggest that both weak and strong motion amplification functions can be assessed by only one strong record which is a confirmation of the results of the previous study.[11] Additionally, the method presented in this paper also demonstrates its ability to trace a non-linear trend by using only one strong earthquake.

The results of analysis from six sites (Chiba, Etchujima, Fujisawa, Samukawa, Shinfuji and TTRL sites) easily identify the reduction in resonance frequency occurring at surface acceleration exceeding roughly 90 gal. It shows that a significant non-linear soil response occurred at these sites. On the other hand, an essentially linear ground response is found in the data from Tomioka site, where peak acceleration up to 130 gal was considered. Tentatively, this is because of stiffer soil condition that can keep the soil response in the linear range.

The other conclusion of this study is an attempt to answer whether the *in situ* dynamic soil behaviour can be duplicated by a laboratory analysis up to large shear strains. The comparison of combined shear modulus – shear strain relationships obtained from all sites (Figure 9) with laboratory results confirm the assumption that *in situ* materials behave similarly. Finally, the consistency in the results of frequency shifting derived from transfer functions (Figures 4 and 7) and calculated shear strain–shear modulus relationships (Figure 8) verified the significance of non-linearity study during strong motions.

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